XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Assessment of the human comfort of steel-concrete composite floors

Jefferson Viana Aguiar[1], Bárbara Elisa Ferreira[2], Hermes Carvalho[2], José Guilherme Santos da Silva[1]

[1]*Civil Engineering Postgraduate Programme (PGECIV), State University of Rio de Janeiro (UERJ)*
São Francisco Xavier St., Nº 524, Maracanã, 20550-900, Rio de Janeiro/RJ, Brazil
jefferson.docm@gmail.com, jgss@uerj.br
[2]*Structural Engineering Department, Federal University of Minas Gerais (UFMG)*
Pres. Antônio Carlos Av., Nº 6627, Pampulha, 31270-901, Belo Horizonte/MG, Brazil.
barbara.elisaf@gmail.com, hermes@dees.ufmg.br

Abstract. This research work aims to investigate the dynamic structural response of steel-concrete composite floors from the point of view of human comfort, when subjected to human walking. This way, the investigated structural model is associated to a steel-concrete composite floor building which is composed of a hot-rolled framing system, with a total area equal to 1300 m². The floor system is used for normal school occupancy and is supported by steel-concrete composite columns with a ceiling height of 3.40m. The proposed numerical model, developed for the floor building dynamic analysis, adopted the usual mesh refinement techniques present in the Finite Element Method (FEM) simulations and implemented in the ANSYS program. In this numerical model, the steel-concrete composite floor girders were represented by three-dimensional beam elements, where flexural and torsion effects are considered. On the other hand, the concrete slab was represented by shell finite elements. Both materials (steel and concrete) present an elastic behavior. The complete interaction between the concrete slab and steel beams was considered in the analysis, i.e., the finite element model coupled all the nodes between the steel beams and concrete slabs, in order to prevent the occurrence of any slip. Regarding the structural behavior of the connections present in the investigated structure, the beam-to-beam connections and the beam-to-column connections were considered as rigid joints. After that, having in mind to determine if the investigated floor framing system satisfies the human comfort criterion for walking vibration, the dynamic structural response of the investigated floor was analysed based on the peak accelerations values. These values were calculated and classified according to several human comfort criteria, considering situations of the current design practice.

Keywords: Steel-concrete composite floors, Dynamic structural analysis, Human comfort assessment.

1 Introduction

The use of slighter and more resistant materials, and observing the construction techniques and processes advance, in addition the structural design development using increasingly faster computers, it became possible to carry out civil engineering constructions with structural systems increasingly slim because the larger free spans necessity. These facts validate that the structural systems of building floors have low values for vibration natural frequencies. In addition, the design of structural systems with low levels of structural damping is observed, related to the kind of materials used, category of construction, non-structural elements presence, age and construction quality [1,2,3,4].

Another important point concerns the multifunctionality that the business market has demanded from current engineering designs, based on the buildings intended use for residential common use spaces, offices and gyms [4], which has contributed to these buildings floors be more susceptible to excessive vibrations arising, mainly, from human activities, such as: walking, jumping, dancing, rhythmic gymnastics and others, generating disturbances to the user with regard to human comfort [1,2,3]. This can be explained for the reason that these human activities present excitation frequencies harmonics close to natural frequencies values of most structures, in the range of 4 to 8 Hz [4,5].

Several authors have developed studies on floor vibrations subjected to human activities. In the research of El-Dardiry and Ji [6], the numerical modelling influence of mixed slabs (steel-concrete), of the steel deck type, on the dynamic structural behavior of a steel building, composed of eight floors, with dimensions of 45m x 21m in plant. In this paper, different modelling strategies were developed, based on the use of isotropic and orthotropic systems and the models dynamic response was evaluated based on comparisons between the values structure natural frequencies obtained via numerical modelling and experimental tests.

Therefore, this investigation has as its central objective numerical modelling and performance of experimental tests to study the mixed floors (steel-concrete) modal parameters, used for school occupation, with total area of around 1300 m², being supported by mixed pillars with 3.40m of ceiling height. In addition, a human comfort analysis of the structural model was carried out according to procedures established in the American Institute of Steel Construction (AISC) design guide [7].

Free vibration experimental tests were made on the floors by means of excitation from controlled jumps close to floor span middle were performed in order to calibrate the results obtained in the numerical modal analysis with the experimental analysis results. Furthermore, forced vibration experimental tests were performed with person’s walking at a normal pace (f_p = 2.0 Hz) in order to assess human comfort based on the limits established in design guides.

2 Investigated structural model

The structural system of investigated floor in this study, used for school occupation, with a total area of approximately 1300 m², shown in Fig. 1, corresponds to a typical example referring to the 8th floor of a mixed building (steel-concrete), with sixteen stories, including engine room, keg, water tank bottom and water tank cover. The design is from a real and existing building, which is under construction. Regarding its use, the building was designed to be a teaching hospital for a private university in Belo Horizonte/MG, Brazil.

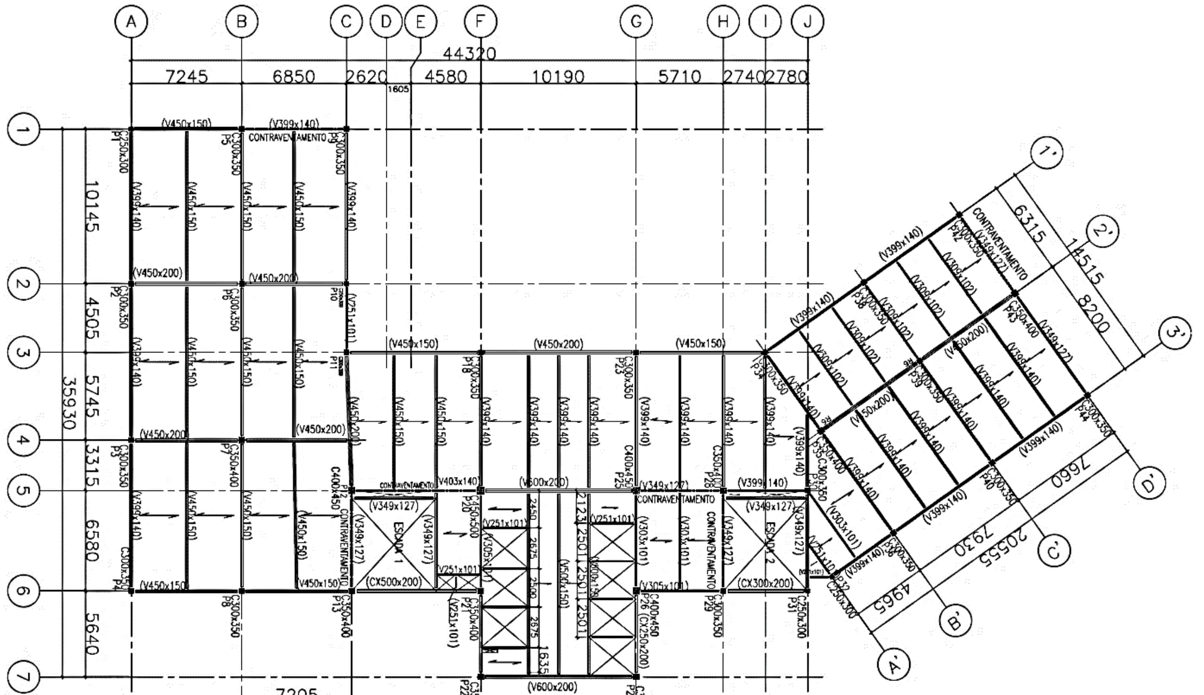


Figure 1. Investigated mixed floor (steel-concrete): 8th floor (dimensions in mm)

The building presents a height between floors of 3.40 meters. The building columns and framework structures consists of welded profiles, with geometric dimensions and properties according to design provided by the construction company, emphasizing that the columns are made of composite steel-concrete welded profiles. The slabs are steel deck type with a total thickness of 15 cm, including the MF75 type shape (7.5 cm high) and the shape thickness which, in this design, can assume values of 0.85 or 0.95 mm. It was considered masonry 1.5 meters high around the entire floor, stairwells and elevator boxes, aiming to simulate in a more realistic way the conditions found in the construction at the experimental tests time. It is a structural masonry, built with a 14x19x29 cm structural ceramic block and filled with grout and steel bars, there is also a concrete top beam.

Regarding the materials used physical characteristics, concrete has a characteristic compressive strength (f_{ck}) equal to 300 kgf/cm², an elastic modulus (E_c) of 380,000.00 kgf/cm², Poisson's ratio (ν_c) equal to 0.2 and specific weight (γ_c) of 2,500.00 kgf/m³; and steel has characteristic yield strength (f_y) of 2,531.05 kgf/cm², modulus of elasticity (E_s) of 2,039,432.40 kgf/cm², Poisson's ratio (ν_s) equal to 0.3 and specific weight (γ_s) of 7,849.05

kgf/m^3. For structural masonry, a longitudinal elasticity module (E_a) of 203,841.27 kgf/cm^2 was adopted, Poisson's ratio (ν_a) equal to 0.15 and specific weight (γ_a) of 1250.00 kgf/m^3, according to criteria established by ABNT NBR 15812-1: 2010 - Structural Masonry - Ceramic blocks Part 1 [8], in the absence of tests or precise information about block characteristics.

3 Finite element modelling

The structural model was analysed using the ANSYS software [9], by the usual discretization techniques associated with the Finite Element Method (FEM). Thus, in the system numerical modelling of steel beams and columns were represented by three-dimensional finite elements BEAM44 [9], where the bending and torsion effects are considered. Steel deck slabs were simulated using finite shell elements. For this simulation the finite shell element SHELL63 [9] was used, which is based on the Thin Plate Theory.

The complete interaction between the steel deck slabs and the steel beams was considered in the study, that is, the numerical model nodes are coupled in order to prevent the occurrence of landslides. The steel and concrete materials are considered to have elastic linear and isotropic behavior, and all sections of the structural model remain flat in the deformed state. The boundary conditions considered restrict as a third-gen support the base and top nodes of the pillars that are half standard height above and below the analysed pavement. The numerical model presents an appropriate refinement degree mesh, in order to allow a good representation of the floor dynamic structural behavior, as illustrated in Fig. 2. It is noteworthy that the beams, columns and slabs have a discretion of 0.50 meters.

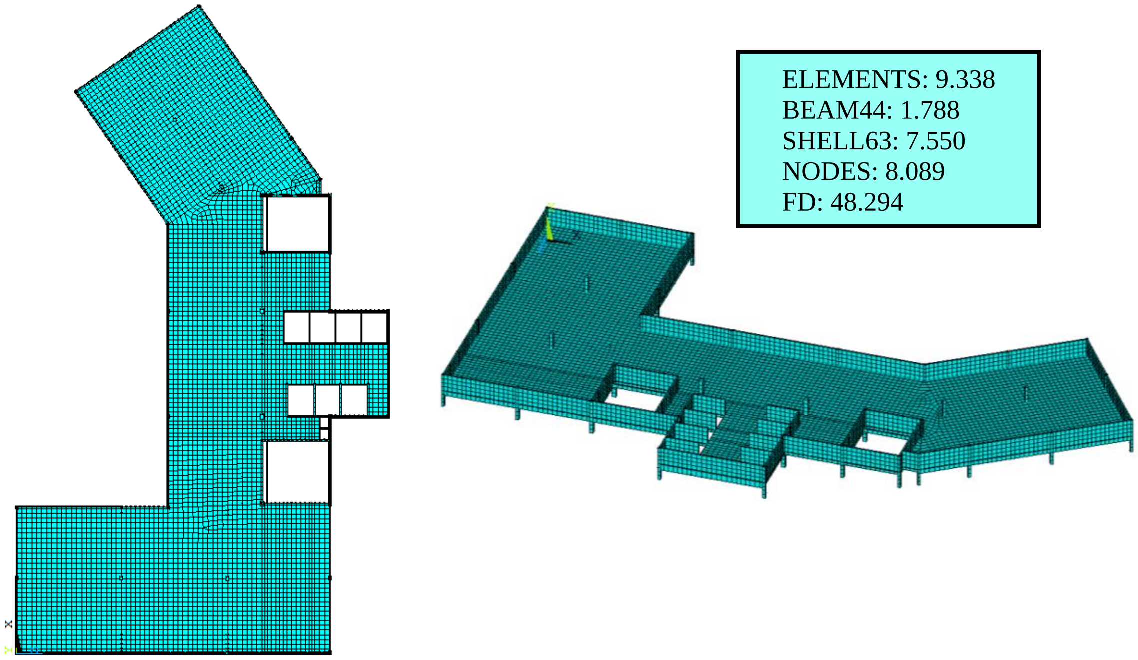


Figure 2. Finite element model of investigated mixed floor (steel-concrete)

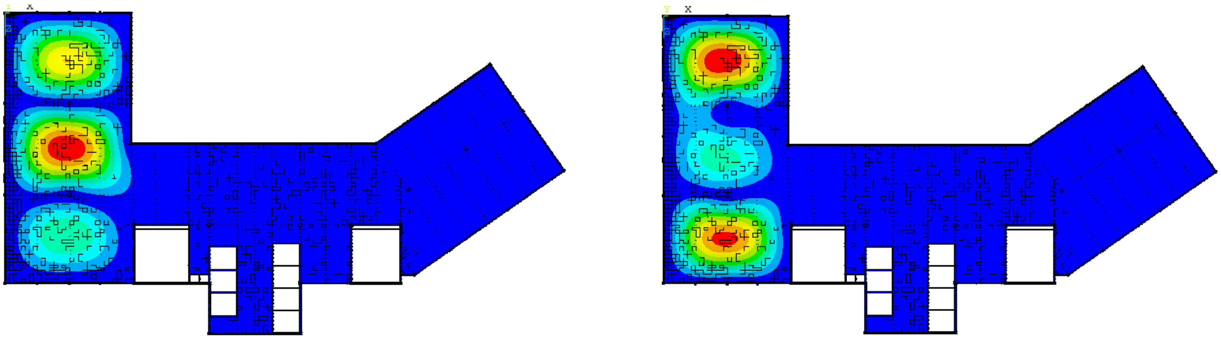
4 Numeric modal analysis: free vibration

This article topic presents the dynamic structural behavior of the system, based on the calculation of natural frequencies, vibration modes and peak accelerations. The modal analysis (free vibration) was performed using the ANSYS software [9], where the natural frequencies (eigenvalues) and their respective vibration modes (eigenvectors) were obtained.

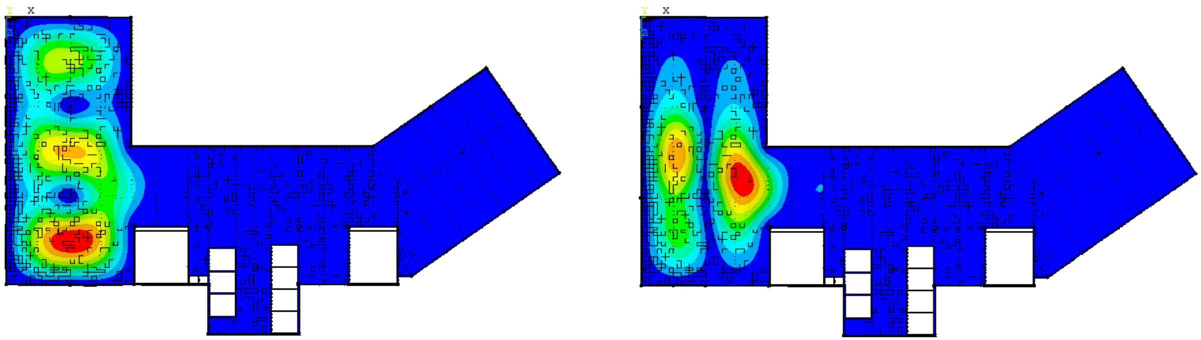
Fig. 3 illustrates the first four slab bending vibration modes and the maximum modal amplitudes, and Table 1 presents the natural frequencies values. It is worth mentioning that these natural frequencies correspond to vibration modes with maximum modal amplitude on strategic slab panels of the structure (Fig. 4), aiming at comparing the natural frequencies values obtained through finite element modelling and by experimental modal analysis with the criteria established by AISC [7] for human comfort.

Table 1. Natural frequencies of the investigated structural model

Vibration mode	Frequency (Hz)	Characteristics
1st	5,71	Bending
2nd	6,49	Bending
3rd	6,87	Bending
4th	7,60	Bending
5th	8,71	Bending
6th	9,24	Bending



a) 1st vibration mode: f_{01} = 5,71 Hz b) 2nd vibration mode: f_{02} = 6,49 Hz



c) 3rd vibration mode: f_{03} = 6,87 Hz d) 4th vibration mode: f_{04} = 7,60 Hz

Figure 3. First four bending vibration modes of the studied floor

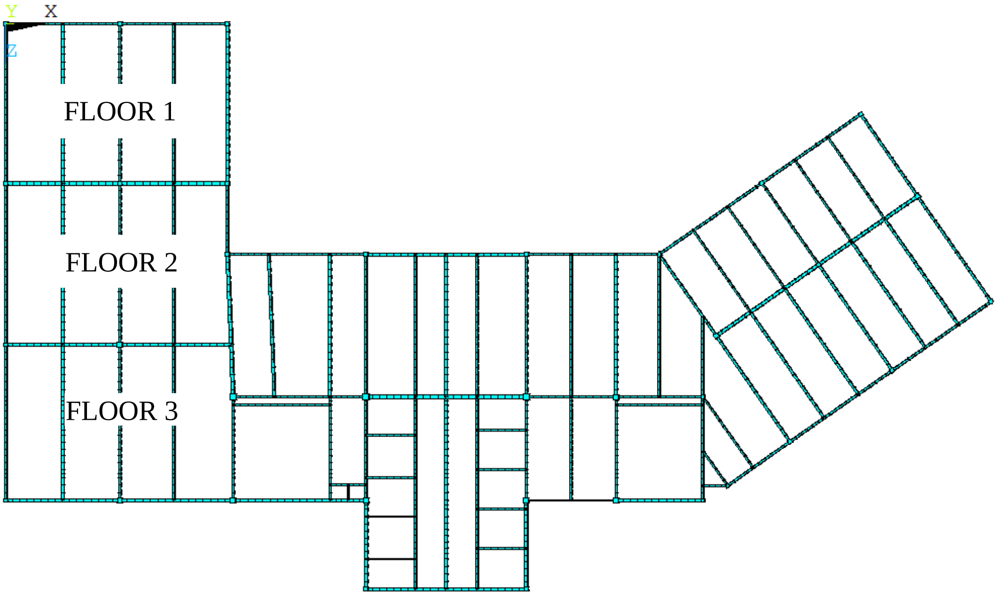


Figure 4. Floors chosen for experimental analysis of the modal parameters

5 Experimental modal analysis: free vibration

The experimental modal analysis was performed through dynamic experimental monitoring, in the place, through the seismic accelerometers installation of the brand PCB Piezotronics, model 393B04, connected to a data acquisition system (brand Bruel and Kjaer, model 3050-A -060), which was connected to a portable computer, responsible for reading and writing the structure response in the time or frequency domain.

The free vibration test was performed in such a way that floors 1, 2 and 3 (Fig. 5) were excited by a 106.2 kg person impact, wearing boots with flexible plastic soles, jumping in their respective floor's centers, at a height of 0.48 m (height of the wooden seat used as a platform). The method used in this test was single input and multiple output data (SIMO).

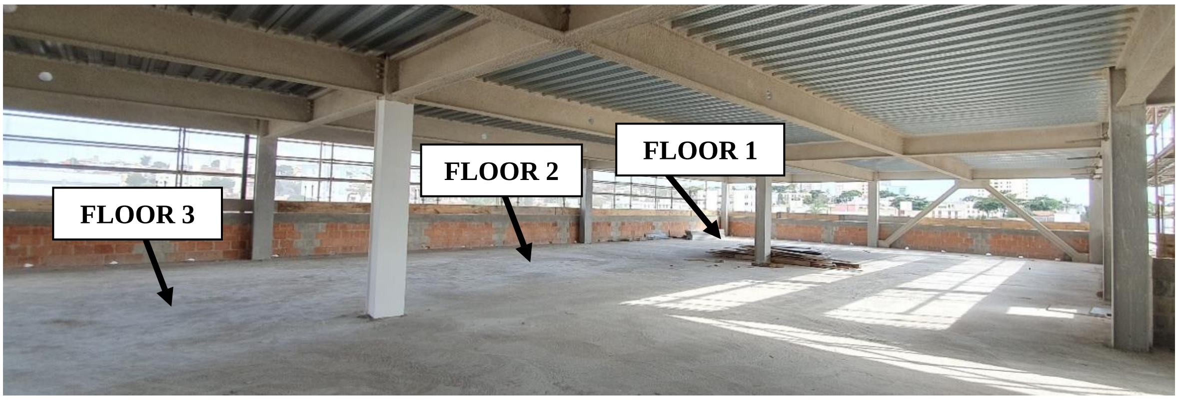


Figure 5. Floors chosen to carry out the experimental tests

Fig. 6 presents the experimental results of frequency domain from the readings performed on the structural model, free vibration, in order to identify the eigenvalues that most collaborate with floors selected vibrations for analysis, which are not reported to the transfer power for quick system response. It is important to note that since the impact load of the jump was not measured, it was not possible to obtain the FRF (Frequency Response Function) for each point in this test. However, how floors natural frequencies are identified through the dynamic response FFT (Fast Fourier Transform) of investigated points.

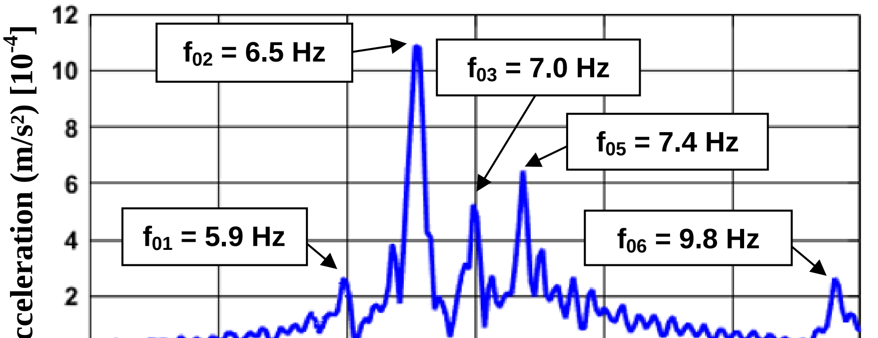


Figure 6. Example of frequency domain response for Floor 1 obtained by experimental measurement

The structure modal damping coefficients for the first six bending modes were obtained by the logarithm decrement method, being, respectively, 1,26% (1st mode), 1,03% (2nd mode) and 1,19% (3rd mode).

Analysing the same Figure 6 graph for all floors, it appears that it is possible to identify the peaks of main frequencies corresponding to the six vertical structure vibration modes for the three tests performed. It is observed that the fourth vibration mode does not manifest itself in the floor 1 and floor 3 test responses obtained, which was already expected, because as can be seen in Figure 3, this mode has a low oscillation range on the floors mentioned, being difficult to differentiate in relation to noise signals. The same is observed and justified for the fifth floor 2 vibration mode.

Based on the presented values in Table 2, it is noted that the experimental results obtained for the three floors have a good agreement with each other, as well as when compared to the numerical results, except for the fifth mode of vibration which presents a difference from the numerical result in relation to the floors 1 and 3 experimental of approximately 18% and 9%, respectively.

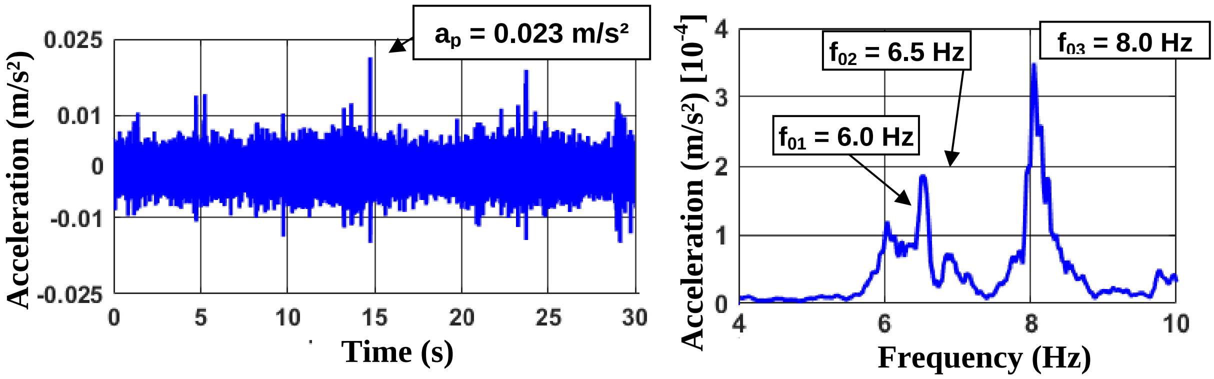
Table 2. Comparison of the obtained values natural frequencies

Mode Shape (See Fig. 3)	Natural Frequencies (Hz)				Difference (%)		
	Numerical Modelling	Experimental test					
		Floor 1	Floor 2	Floor 3	Floor 1	Floor 2	Floor 3
1st	5.71	5.9	5.9	5.9	3.22%	3.22%	3.22%
2nd	6.49	6.5	6.5	6.5	0.15%	0.15%	0.15%
3rd	6.87	7.0	6.9	7.0	1.86%	0.43%	1.86%
4th	7.60	-	8.0	-	-	5.00%	-
5th	8.71	7.4	-	8.0	-17.70%	-	-8.88%
6th	9.24	9.8	-	8.9	5.71%	-	-3.82%

6 Experimental dynamic analysis: forced vibration

The dynamic structural response of the floor was obtained based on the use of a metronome and considering the human walking. The metronome's representative unit is "*bpm*" (beats per minute). Thus, each sound "*beat*" corresponds to the contact of each person's step on the structure.

To perform the test, the metronome value was set at 120 bpm (f_p = 2.0 Hz), which corresponds to a person walking normally. The results obtained are shown in Fig. 7, described in the time and frequency domain, respectively. These results correspond to the accelerometer installed on the middle of each investigated floor (1, 2 and 3: see Fig. 4).



a) Time domain b) Frequency domain

Figure 7. Example of forced vibration test on Floor 1 (Normal walk: f_p = 2.0 Hz)

7 Human comfort assessment

The study floors suitability was verified when subjected to human walking, with regard to discomfort related to vibrations. Thus, the accelerations maximum values found in the experimental dynamic analysis were compared with the limit values proposed by AISC guide [7] and are presented in Table 3.

Table 3. Human comfort analysis by experimentally obtained accelerations.

Experimental Test	Peak Acceleration (m/s²)	Human Comfort AISC [7]
Test Floor 1: normal walk	0.023	OK
Test Floor 2: normal walk	0.019	OK
Test Floor 3: normal walk	0.049	OK

The AISC project guide [7] provides fundamental principles and simple analysis tools to evaluate floor systems subjected to human activities, stipulating the 0.5% of gravity acceleration as the peak acceleration limit for steel-concrete composite floors [$a_{lim} = 0.5\ g = 0.049\ m/s^2$].

It can be seen from Table 3 results that human comfort criteria proposed by the AISC design guide [7] were satisfied for the all investigated floors considering one people in normal walking ($f_p = 2.0$ Hz). However, it is interesting to note that, according to Bachmann [10], a person standing can notice a peak acceleration value equal to 0.034 m/s² (perceptible) and 0.1 m/s² (clearly perceptible).

8 Conclusions

This research investigated the dynamic structural response of a mixed floor (steel-concrete), from the point of view of human comfort, submitted to human walking. The structural model analysed concerns a mixed floors (steel-concrete) system, used for school occupation, with a total area of 1300 m². Thus, the main conclusions are:

1. The finite element model proved to be calibrated in relation to experimental modal analysis data. The differences between numerical model and experimental monitoring were mostly below 5%, except for the fifth and sixth vibration modes.
2. Regarding the peak accelerations values, related to the central section of each tested floors, it was found that structure does not surpass the limit proposed by AISC design guide [7], when the human walking is considered.
3. In sequence of the investigation, it is the author's intention to develop more experimental tests and also an extensive numerical study about the evaluation of the people-floor dynamic interaction effect, based on the use of biodynamic models, aiming to better evaluate the dynamic structural behaviour for steel-concrete composite floors under human walking.

Acknowledgements. The authors gratefully acknowledge the financial support for this research work provided by the Brazilian Science Foundation's CNPq, CAPES and FAPERJ.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Campista, F. F., 2019. *Modelagem de sistemas biodinâmicos para avaliação do comportamento estrutural dinâmico de pisos mistos (aço-concreto) de edifícios submetidos a atividades humanas rítmicas*. PhD Thesis of the Civil Engineering Post-graduate Programme, PGECIV. State University of Rio de Janeiro, UERJ. Rio de Janeiro/RJ, Brazil.

[2] Campista, F.F.; Gaspar, C.M.R. & Santos da Silva, J.G., 2015. Modelagem das ações humanas rítmicas e estudo do conforto humano sobre edifícios mistos (aço-concreto). In: *XXXVI Iberian Latin-American Congress on Computational Methods in Engineering (CILAMCE 2015)*, pp. 1-16, Rio de Janeiro/RJ, Brasil.

[3] Gaspar, C. M. R.; Da Silva, J. G. S. (2015), Influence of the human rhythmic activities modelling on the composite floors dynamic response. In: *Journal of Civil Engineering and Architecture Research*, vol. 2, no 1, pp. 429-437.

[4] Aguiar, J. V., 2017. *Modelagem do comportamento estrutural dinâmico e avaliação dos critérios de projeto para conforto humano de edifícios submetidos a ações humanas rítmicas sobre os pisos*. Masters dissertation of the Civil Engineering Post-graduate Programme, PGECIV. State University of Rio de Janeiro, UERJ. Rio de Janeiro/RJ, Brazil.

[5] Murray, T. M.; Allen, D. E.; Ungar, E. E., 2003. Steel design guide series 11: Floor vibrations due to human activity, 2nd printing. Chicago, USA: *American Institute of Steel Construction (AISC).*

[6] El-Dardiry, E.; Ji, T., 2006. Modelling of the dynamic behaviour of profiled composite floors. *Journal of Engineering and Structures*, v. 28, pp. 567-579.

[7] Murray, T. M. et al., 2016. Steel design guide series 11: Vibrations of steel-framed structural systems due to human activity, 2nd Edition. 1st Printing. Chicago, USA: *American Institute of Steel Construction (AISC).*

[8] *ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS*, 2010. ABNT NBR 15812-1: Alvenaria estrutural – Blocos cerâmicos. Parte 1: Projetos. Rio de Janeiro. 41 p.

[9] ANSYS Swanson Analysis Systems Inc., 2009. *Theory Reference* (release 12.1).

[10] Bachmann, H. et al., 1995. Vibration problems in structures - practical guidelines. *Basel (Switzerland):Institut für Baustatik und Konstruktion*, Birkhäuser.